Progress In Electromagnetics Research Letters, Vol. 17, 153–161, 2010

SINGLE METAL LAYER CPW METAMATERIAL BANDPASS FILTER

I. A. I. Al-Naib, C. Jansen, and M. Koch

Physics Department
Philipps-Universität Marburg
Renthof 5, Marburg 35032, Germany

Abstract—We propose single metal layer metamaterial bandpass filters based on compact complementary u-shaped resonators. Previously, metamaterial bandpass filters could only be achieved if a second conducting layer was utilized. Here, we propose a resonator concept that can directly be integrated with a single sided coplanar waveguide, enabling low fabrication costs and simple system integration. Furthermore, already a single unit cell yields a pronounced bandpass behavior without the need for cascading multiple resonators. Both, measurements and numerical simulations are presented. Using RO3003 as substrate, a low insertion loss of 1.71 dB and a corresponding 3-dB bandwidth ratio of 3.1% is achieved.

1. INTRODUCTION

Recent years have seen an unprecedented growth in the deployment of wireless communication systems. The ongoing development in this field is driven by the need for higher data rates as more and more bandwidth-demanding applications become available. Passive microwave elements, especially RF-filters, are the key components of modern wireless communications. Transceiver modules, for example, rely on bandpass filters to separate uplink from downlink. To succeed in this field, on top of a good filter performance and low fabrication costs, miniaturization is a major concern to achieve a high integration density [1].

While conventional microwave circuits are usually realized in microstrip technology, coplanar waveguide (CPW) designs prove to

Received 11 August 2010, Accepted 14 September 2010, Scheduled 20 September 2010
Corresponding author: I. A. I. AL-Naib ((ibraheem.alnaib@staff.uni-marburg.de).

be advantageous when integration with lumped or active components is required. In addition to that, CPW technology offers low dispersion and simple realization of short-circuited ends without the need of vias, which leads to the reduction of the radiation losses and the fabrication effort [2, 3].

Over the past decade, metamaterials, a novel class of artificial materials, have become a field of active research in many branches of science. Metamaterials are by definition much smaller than the wavelength and can offer unique electrodynamic properties, not available in any natural material [4–6].

Split ring resonator (SRR) based bandstop filters integrated with a CPW have been accomplished by placing the magnetically excited SRRs on the backside of the substrate centered beneath gaps in the CPW [7–9]. A bandpass response can be obtained by adding metallic strips on the upside of the substrate, connecting the center conductor to the ground planes [10–15]. Yet, both designs require two metallization layers. Furthermore, multiple pairs of SRRs will be necessary to obtain an acceptable out-of-band suppression [10]. In 2004, Falcone et al. proposed single-layer bandstop filters by placing the split ring resonators inside the CPW slots. However, the wide slot size required for such an approach lead to a considerable mismatch and a poor device performance. Recently, metamaterial bandstop have been demonstrated which utilize complementary SRRs. This approach enables a high filter performance as a good matching between the CPW and the resonators is achieved while the advantages of a single-layer design are maintained [16]. However, obtaining a bandpass response from a single-layer SRR-based structure seems to be hard to accomplish so that alternative metamaterial concepts have to be explored.

In this paper, we demonstrate a single metal layer metamaterial bandpass filter based on complementary u-shaped resonators (CUSRs). The structures exhibit a bandpass response with low insertion loss and high stopband attenuation. Furthermore, we show that strip line stubs in the vicinity of the resonators can be employed to easily optimize the insertion loss or the resonator bandwidth. Both, measurements and corresponding numerical simulations are presented.

2. THE PROPOSED STRUCTURE

Figure 1(a) shows a photograph of the proposed metamaterial filter. A standard mask/photoetching technique is employed to fabricate the structures using a commercial substrate (RO3003, dielectric constant $\varepsilon_r = 3$, thickness $h = 013\,\mathrm{mm}$, $\tan\delta = 0.00134$). Fig. 1(b) shows a schematic of the CUSR unit cell. The dimensions of the CUSRs

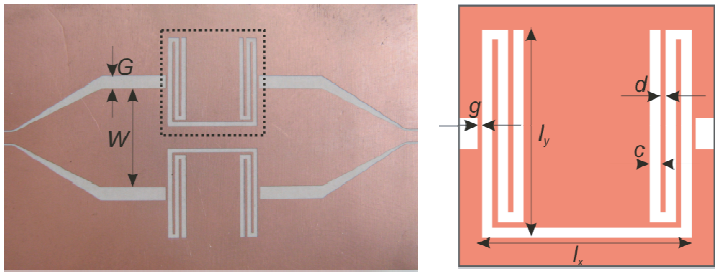

Figure 1. (a) Photograph of CUSR based metamaterial bandpass filter integrated with a CPW and (b) a schematic of a CUSR unit cell with its corresponding dimensions.

are chosen such that the device operates in the C-band around 4 GHz resulting in a width of $c = 0.45$ mm, a separation of $d = 0.15$ mm, a strip line width of $g = 0.1$ mm, and an outer resonator length of $l_x = l_y = 7.8$ mm. Finally, the resonator spacing is 10 mm and the lateral dimensions of the host CPW (W, G) have been selected to obtain a 50 Ω characteristic impedance with a relatively wide center conductor to accommodate the CUSR-pairs. Tapers adapt the CPW to a fixture (Wiltron 3680), which avoids measurement errors often induced by soldered connectors. The measurements have been conducted using a vector network analyzer (VNA-8510) from Agilent. A CPW thru-short-line kit was employed to calibrate the VNA. It is found that the return loss is better than 40 dB and the insertion loss is bouncing between 0 and 0.04 dB for the thru calibration component. A commercially available 3D full-wave solver (Ansoft HFSS) based on the finite element method is employed to calculate the S-parameters [17]. All the simulations in this paper consider a lossy substrate with the aforementioned parameters.

3. RESULTS

Figure 2 shows the simulated (dashed line) and the measured (solid line) return (S_{11}) and insertion (S_{12}) losses. The simulations agree very well with the measurements. Only small quantitative discrepancies are observed, which can be attributed to manufacturing inaccuracies. At the centre frequency of $f_c = 3.75$ GHz, the simulated and measured return loss is 15.1 dB and 14.8 dB, respectively. The corresponding insertion losses are 1.65 dB and 1.71 dB, respectively. The bandwidth ratio, defined as the 3-dB bandwidth normalized to the centre

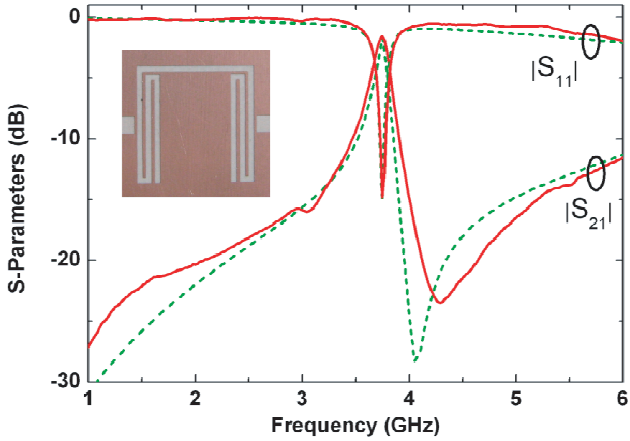

Figure 2. Simulated (dashed line) and measured (solid line) return and insertion losses of a single cell CUSR based bandpass filter.

frequency, is experimentally determined to 3.1%. Moreover, the next adjacent resonance occurs at 7.45 GHz with a wide band separation of 3.7 GHz from the design frequency. For most applications, cascading of the presented structures, as it has been proposed for double sided SRR based filters [10], will not be necessary as a single cell already exhibits a very pronounced bandpass behavior. Please note, that besides the advantages due to the single metallization layer and the good filter performance, the investigated structure also features very compact lateral dimensions of approximately 10% of the guided wavelength λ_g.

The underlying physical mechanism can be intuitively understood in the framework of a circuit model. Such a model for the upper half of the symmetric structure is shown in Fig. 3. L and C are the per-section inductance and capacitance of the line. The CUSR is modeled here for simplicity as a parallel resonator constituted by a capacitance C_u and an inductance L_u. The strip line is considered in form of the inductance L_{sl}. In front of the resonator we have two slots. One of them is in the center conductor and the other one is in the ground. The slot in the center conductor can be modeled as an inductance with capacitance in parallel. The slot in the ground conductor has the same effect, yet, the absolute value of the inductance and capacitance may be a bit different [18, 19]. Together the two slots form a simple resonance circuit shown in Fig. 3 by a dashed box. After the resonator we have a second pair of slots.

A resonance frequency shift towards higher frequencies with

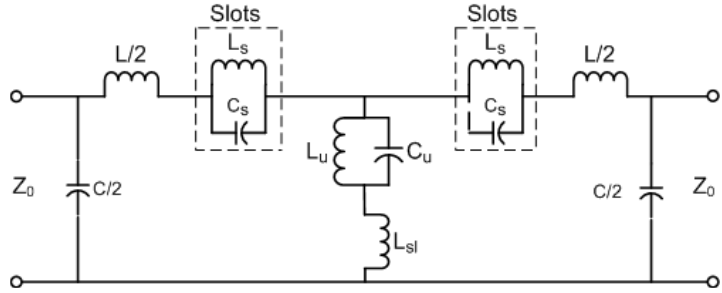

Figure 3. Equivalent-circuit model for the CUSR-slots.

increasing c is observed, which is attributed to the decreased capacitance C_u due to the increased distance between the neighboring metal strips. Doubling the width c induces an 8% shift in the center frequency. Increasing d yields a higher inductance L_u and consequently increases the losses. However, the lower frequencies experience higher impedance, which leads to a narrower bandwidth. A small strip line length g results in low insertion losses, which can be explained by the balancing of the inductive ($L_u + L_u$) and the capacitive (C_{sl}) contributions. This behavior saturates towards high values of g.

To further understand the details of the resonator concept, we will consider the Smith chart shown in Fig. 4. Smith charts are commonly used to study impedance matching problems in optical and microwave filters [20, 21]. Each trace in Fig. 4 represents a frequency sweep of the resonator impedance Z_{Res} normalized to the line impedance Z_L from 2 GHz (solid squares) to 5 GHz (arrow tips). The center of the Smith chart marks the point of perfect matching where $Z_{Res}/Z_L = 1$. The crosses denote the center frequency of each resonator.

Our investigations will focus on the influence of two crucial design parameters on both the bandwidth and the losses. The first parameter is the strip line width g (cf. Fig. 1), which has a high impact on the coupling between the line and the resonator. Comparing two cases, once with $g = 3$ mm (dotted line) and once with $g = 0.1$ mm (dashed line) in the Smith chart, we find that increasing g sharpens the resonance (smaller circle) but also results in a considerable mismatch which leads to an increased insertion loss at the design frequency. Furthermore, we observe that the resonance frequency shifts from 3.75 GHz in the case of $g = 0.1$ mm to 3.81 GHz in case of $g = 3$ mm. All three findings can be explained by the additional inductance introduced by elongating the strip line. Thus, if low losses are the primary design objective, g should be chosen as small as supported by the fabrication process, which in our case is 100 µm (cf. Fig. 2).

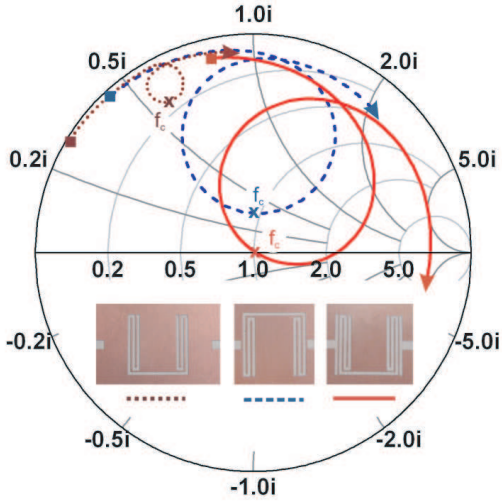

Figure 4. Smith chart of a CUSR-CPW structure with a strip line width of $g = 3\,\text{mm}$ (dotted curve), $g = 0.1\,\text{mm}$ (dashed curve) and a reactive slot with a length of $sl = 8\,\text{mm}$ (solid curve). The corresponding resonance frequencies are 3.81 GHz, 3.75 GHz, and 3.68 GHz, respectively.

Besides altering the strip line width g, adding slots in the vicinity of the resonator provides another lever for optimizing the impedance matching by introducing an additional capacitive load. The solid curve in Fig. 4 represents the case of a slot with a length of $sl = 8\,\text{mm}$. A slight increase in the bandwidth ratio is observed (bigger circle). However, the point marking the center frequency is now positioned very close to the origin of the Smith chart so that nearly perfect matching is achieved. In this optimized case, Ohmic and substrate losses constitute the main loss factors.

To further investigate the tradeoff between losses and the bandwidth ratio, we sweep sl between 2 mm and 8 mm. As shown in Fig. 5, the insertion loss decreases with increasing slot length, while the bandwidth ratio is increased. For example, a slot length of $sl = 6\,\text{mm}$ results in an insertion loss of less than 1 dB with a bandwidth ratio of less than 12%. Exploring this additional degree of freedom in the design of CUSRs enables custom tailored filter characteristics by varying only a single geometrical parameter of the structure.

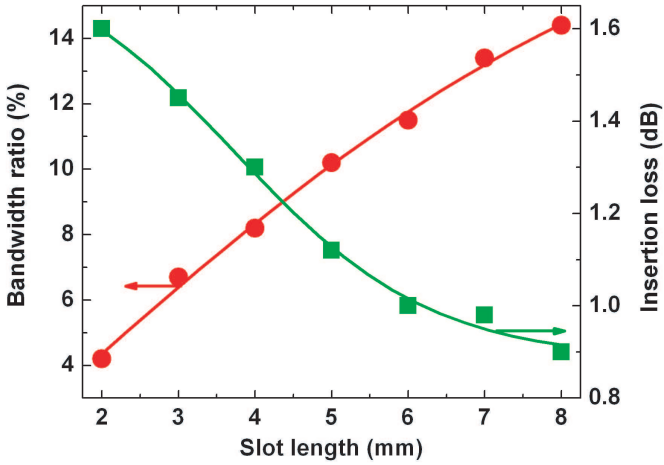

Figure 5. Measured bandwidth ratio (left scale) and insertion loss (right scale) for a sweep of slot lengths *sl* from 2 mm to 8 mm.

4. CONCLUSION

To conclude, we demonstrate CPW integrated metamaterial bandpass filters based on complementary u-shaped resonators which require only a single metallization layer. The resonators feature a very low insertion loss, a good bandwidth ratio and a strong out-of-band rejection. Furthermore, with a lateral unit cell dimension of approximately 10% of the guided wavelength, the resonators feature a very small electrical size. A good agreement between numerical simulations and experimentally obtained data was observed. CUSR based single metal layer bandpass filters hold a great potential for many applications including transceiver front-end designs for high-speed communication systems.

ACKNOWLEDGMENT

The authors would like to thank Prof. Jörg Schöbel from the TU Braunschweig for his ongoing support and valuable discussions.

REFERENCES

1. Liao, S., P. Sun, H. Chen, and X. Liao, "Compact-size coplanar waveguide bandpass filter," *IEEE Microwave and Wireless Components Letters*, Vol. 13, No. 6, 241–243, 2003.
2. Simons, R. N., *Coplanar Waveguide Circuits, Components, and Systems*, Wiley-IEEE Press, 2001.
3. Wolff, I., *Coplanar Microwave Integrated Circuits*, Wiley-Interscience, 2006.
4. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics Uspekhi*, Vol. 10, No. 4, 509–514, 1968.
5. Pendry, J. B., A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory and Technology*, Vol. 47, 2075–2084, 1999.
6. Shelby, R. A., D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, Vol. 292, 77–79, April 2001.
7. Martin, F., F. Falcone, J. Bonache, R. Marques, and M. Sorolla, "Miniaturized coplanar waveguide stop band filters based on multiple tuned split ring resonator," *IEEE Microwave Wireless Components Letters*, Vol. 13, 511–514, 2003.
8. Al-Naib, I. A. I., C. Jansen, and M. Koch, "Compact CPW metamaterial resonators for high performance filters," *Passive Microwave Components and Antennas*, Vitaliy Zhurbenko (ed.), Chapter 20, Intech, 2010.
9. Al-Naib, I. A. I. and M. Koch, "Coplanar waveguides incorporating SRRs or CSRRs: A comprehensive study," *Progress In Electromagnetics Research B*, Vol. 23, 343–355, 2010.
10. Martin, F., J. Bonache, F. Falcone, M. Sorolla, and R. Marques, "Split ring resonator based left-handed coplanar waveguide," *Applied Physics Letters*, Vol. 83, No. 22, 4652-1–3, 2003.
11. Crnojević-Bengin, V., V. Radonić, and B. Jokanović, "Left-handed microstrip lines with multiple complementary split-ring and spiral resonators," *Microwave and Optical Technology Letters*, Vol. 49, No. 6, 1391–1395, 2007.
12. Ibraheem, I. A., J. Schoebel, and M. Koch, "Group delay characteristics in coplanar waveguide left-handed media," *Journal of Applied Physics*, Vol. 103, 024903-1–7, 2008.
13. Al-Naib, I. A. I., C. Jansen, and M. Koch, "Miniaturized bandpass

filter based on metamaterials resonators: A conceptual study," *Journal of Physics D: Applied Physics*, Vol. 41, No. 20, 205002, 2008.

14. Isik, O. and K. P. Esselle, "Design of monofilar and bifilar Archimedean spiral resonators for metamaterial applications," *IET Microw. Antennas Propag.*, Vol. 3, No. 6, 929–935, 2009.
15. Borja, A. L., J. Carbonell, V. E. Boria, and D. Lippens, "Highly selective left-handed transmission line loaded with split ring resonators and wires," *Applied Physics Letters*, Vol. 94, No. 143503, 2009.
16. Ibraheem, I. A. and M. Koch, "Coplanar waveguide metamaterials: The role of bandwidth modifying slots," *Applied Physics Letters*, Vol. 91, 113517-1–3, 2007.
17. Ansoft HFSS®, http://www.ansoft.com.
18. Dib, N. I., L. P. B. Katehi, G. E. Ponchak, and R. N. Simons, "Theoretical and experimental characterization of coplanar waveguide discontinuities for filter applications," *IEEE Trans. Microwave Theory and Technology*, Vol. 39, No. 5, 873–882, 1991.
19. Ponchak, G. E. and L. P. B. Katehi, "Open- and short-circuit terminated series stubs in finite-width coplanar waveguide on silicon," *IEEE Trans. Microwave Theory and Technology*, Vol. 45, No. 6, 970–976, 1997.
20. MacLeod, H. A., *Thin-film Optical Filters*, Taylor & Francis, 2001.
21. Pozar, D. M., *Microwave Engineering*, John Wiley and Sons, 2005.